Int. J. Thermal-Fluid Engineering and Modern Energetics 1 (2022) 34-47 www.tfeme-ba.com
doi: 10.51558/2831-0527.2022.1.1.34

Article

Thermo-hydraulic Performance Analysis of Al_2O_3/water Nanofluid Flow in a Tube Extended by Twisted Tape

Emrehan Gürsoy*[1], Ezgi Çalar[2], Abdullah Dağdeviren[1], Hayati Kadir Pazarlıoğlu[3], Engin Gedik[4], Kamil Arslan[5]

[1]*Department of Energy Systems Engineering, Institute of Graduate Programs, Karabük University, Karabük, Türkiye*
[2]*Department of Mechanical Engineering, Institute of Graduate Programs, Karabük University, Karabük, Türkiye*
[3]*Aselsan Inc., Microelectronics Guidance and Electro-Optics Business Sector, Ankara, Türkiye*
[4]*Department of Energy Systems Engineering, Faculty of Technology, Karabük University, Karabük, Türkiye*
[5]*Department of Mechanical Engineering, Faculty of Engineering, Karabük University, Karabük, Türkiye*

*Corresponding author: e-mail: 2038172002@ogrenci.karabuk.edu.tr

A R T I C L E I N F O

Article history:

Available online 1 July 2022

Keywords:

CFD
Convective heat transfer
Laminar flow
Al_2O_3/water
Twisted tape

A B S T R A C T

In this numerical study, heat transfer characteristics and hydrodynamical analysis have been performed for a circular tube inserted with twisted tape, which has different twisted pitch ratios (*TPR*=0, 50, 100, and 200). As a working fluid Al_2O_3/water nanofluid is used which has different volumetric concentrations ($0.0 \leq \varphi \leq 3.0$ *vol. %*). The numerical analysis has been carried out under the constant wall heat flux (q'') of 4357 W/m^2 for laminar flow ranging the Reynolds (*Re*) number from 1000 to 2000. According to numerical results, the highest average Nusselt number (*Nu*) and average Darcy friction factor (*ff*) have realized in twisted pitch ratio (*TPR*) 50. The reason is that when the twisted pitch ratio gradually decreases, stronger secondary flows and a higher velocity can be obtained. When compared with water, the highest *Nu* for *TPR*=50 has been obtained at φ=3.0 *vol. %* concentration as 61.15%. Also, when compared with *TPR*=0, the highest thermal performance enhancement (TPE) was realized at *φ*=3.0 *vol. %* concentration and *Re*=2000 conditions as 61.15% for *TPR*=50.

Nomenclature		*Greek Symbols*	
D	diameter (mm)	φ	volume concentration of nanoparticle (%)
ff	average Darcy friction factor	μ	dynamic viscosity (kg/ms)
L	length (mm)	ρ	density (kg/m^3)
Nu	average Nusselt number	*Subscripts*	
P	pressure (Pa)	b	bulk
Re	Reynolds number	b_f	base fluid
T	temperature (K)	h	hydraulic
TPE	thermal performance enhancement	in	inlet
TPR	twisted pitch ratio	n_f	nanofluid
q”	heat flux (W/m^2)	n_p	nanoparticle
V	velocity (m/s)	w	wall

1. Introduction

The depletion of fossil fuels, increasing energy demand, and limited sources caused improving the systems in order to sustainable energy. One of these improvement applications is the heat transfer improvement studies on the heat exchanger, which is widely used in industry [1]–[4]. So, in order to reach high heat transfer capacities passive and active methods are applied to the heat exchangers and there are so many applications in the literature [5][6]. The passive method does not require mechanical or electrical power and usually involves inserting fins of different shapes or nanofluids with different contents or using both methods together. For this reason, the passive method is preferred more than the active method in applications [7][8].

Applications and research related to adding nanoparticles to conventional fluids such as known water, oil, and ethylene glycol have increased in recent years [9][10]. Nanofluids are used in spray cooling systems [11], detergent application [12], automobile applications [13], electronic device cooling [14], and solar thermal applications [15]. One of the other passive techniques is the use of modifications in surfaces and geometries in a flow tube. For that purpose, turbulators are inserted into a channel for enhancing the convective heat transfer. When a literature search is done, most of the studies were generally classified as ribs, baffles, twisted tape, wire coil, and vortex generators [16]. Initially, although inserting such complex geometries was difficult, nowadays, with the help of developing its fabrication techniques applying new geometries is more possible. Recently, research on twisted tape inserted in a tube gradually increased and a lot of studies exhibited that the most effective way to enhance the convective heat transfer is twisted tape geometries [17], [18]. He et al. [19] numerically investigated flow field and heat transfer characteristics in a tube that has one and two twisted tapes using CuO/water nanofluids. While the analysis has been simulated single and two-phase models, it has been realized $3{,}000 \leq Re \leq 36{,}000$ turbulent regimes, $\varphi=0.01$, 0.02, 0.03, and 0.04 *vol.%* concentration and different twisted ratios for each phase model. They observed from the analysis that while maximum performance is obtained in two-phase model, $Re=36{,}000$ turbulence regime and $\varphi=0.04$ *vol.%* concentration for both one twisted tape and two twisted tape tubes as 2.18 and 2.04, respectively. Therefore, they concluded that one twisted tape tube is more favorable compared to two twisted tape tubes.

Wongcharee and Eimsa-rad [20] experimentally investigated separately the friction and thermal performance of CuO/water nanofluid at the circular tube which has typical twisted tape and alternate axis twisted tape. The experiment was conducted under the $830 \leq Re \leq 1990$ flow regime, $0.3 \leq \varphi \leq 0.7$ vol.% concentration and $H/D=3$ constant twisted ratio. They obtain from results that the Nusselt number increases with increasing Reynolds number and nanofluid concentration. Also, they have found that while compared to the smooth tube, the typical twisted tape and alternate axis twisted tape increased the Nusselt number up to 7.2 and 12.8 times, respectively. Eimsa-ard and Kiatkittipong [21] experimentally and numerically scrutinized the heat transfer enhancement of a heat exchanger which has multiple twisted tapes in different arrangements and TiO_2 nanoparticles with different concentrations. Studies have been done under $5{,}400 \leq Re \leq 15{,}200$ turbulence regime and $0.07 \leq \varphi \leq 0.21$ vol.% concentrations. They found that as compared to smooth tube, multiple twisted tapes show superior heat transfer. Also, it has been found that arrangement of twisted tapes in the counter current was superior energy saving device for the practical use in condition that low Reynold number. When compared to the smooth tube with water as the working fluid, the tube inserted with quadruple co-tapes as co-quadruple swirl flow generators with TiO_2/water nanofluid at 0.21 *vol.%* exhibited the highest thermal performance factor 1.59, where heat transfer rate and friction factor increased to 3.52 and 11.7 times, respectively.

Bahiraei et al. [22] numerically researched second law analysis of GNP–Pt/water hybrid nanofluid in tubes equipped with double twisted tape which develops diverse swirling flow inserts. The study has realized turbulence flow regime and $0.0 \leq \varphi \leq 0.1$ vol.% concentrations conditions. They have concluded that in the case of using double counter twisted tapes, by decreasing the twisted ratio from 3.5 to 2.5 at a concentration of 0.06 *vol.%*, the global thermal entropy generation rate reduces by around 10%.

Also, in the case of double co-twisted tapes with a twisted ratio of 3, increasing the concentration from 0.0 *vol.%* to 0.1 *vol.%* causes a 14% decrement in the global thermal entropy generation rate. Azmi et al. [23] carried out an experiment aiming to reveal the effect of TiO_2/water nanofluid flow on the convective heat transfer coefficient and friction factor in a tube with twisted tape inserts. The experiment has been conducted under $5,400 \leq Re \leq 15,200$ turbulence regime and $0.07 \leq \varphi \leq 0.21$ *vol.%* concentrations conditions. Researchers found that with the use of twisted tapes, the heat transfer coefficient increased with a decrease in twist ratio for water and nanofluid. Also, the most enhancement is realized as 23.2% in twisted tape tubes. Aghayari et al. [24] experimentally and numerically investigated the performance of a twisted-tape inserted double-pipe heat exchanger using Fe_2O_3/water nanofluid. Different parameters such as mass flow rate, twist ratio of tape, temperature, and volumetric concentration. As parameters, 0.08-0.1 *vol.%* concentration, $2.5 \leq H/D \leq 5.2$ twist ratios and $5,000 \leq Re \leq 28,500$ turbulence flow regime. The obtained results show that increasing nanofluid concentration, as well as twisted-tape inserts, increases heat transfer and Nusselt number.

Li et al. [25] researched entropy generation and forced convection heat transfer of Al_2O_3/water nanofluid in a heat exchanger equipped with helical twisted tape, numerically. They have reported the effect of *Re number*, pitch ratio, and height ratio on entropy generation. According to the result, they concluded that whereas thermal entropy generation decreases with the rise of height ratio and *Re number*, frictional entropy generation increases with the rise of pitch ratio. Farshad and Sheikholeslami [26] numerically investigated energy loss and heat transfer of Al_2O_3/water nanofluid used in the solar collector. While they employed the k-ε turbulence model in the study, *Re number*, pitch ratio and the number of revolutions are variable parameters. According to the result, as the diameter ratio augments, exergy loss drops due to the reduction of surface temperature. Also, increasing inlet velocity causes a significant reduction in surface temperature which results in less exergy loss. As the number of revolutions increases, exergy loss declines while η_{II} rises due to the reduction of temperature at the surface. Sundar and Sharma [27] experimentally investigated turbulent heat transfer and friction factor of Al_2O_3/water nanofluid under $10,000 \leq Re \leq 22,000$ turbulence regime, $0 < H/D < 83$ twist ratios range and $0.02 \leq \varphi \leq 0.2$ *vol.%* concentrations. According to the results of the study, the heat transfer coefficient and friction factor of 0.5 *vol.%* concentration of Al_2O_3/water nanofluid with twist ratio of five is 33.51% and 1.096 times respectively higher compared to the flow of water in the smooth tube.

Safikhani and Abbasi [28] numerically simulated the Al_2O_3/water nanofluid flow in flat tubes inserted with twisted tapes and the study results have been evaluated with three different (circular tube without twisted tape and containing nanofluid, circular tube with twisted tape and containing base fluid and flat tube without twisted tape and containing base fluid) Heat Transfer Enhancement methods. While the analysis has been performed under $100 \leq_{Re} \leq 2,000$ flow regime and $0.0 \leq_{\varphi} \leq 3.0$ $_{vol.\%}$ concentrations, 4 kW/m^2 heat flux has been implemented in the tube wall. The results indicate that although all three mechanisms improve the heat transfer within the tubes, the twisted tape mechanism exhibited more heat transfer enhancement than the other two mechanisms. Prasad and Gupta [29] experimentally researched the heat transfer enhancement behavior of Al_2O_3/water nanofluid using in U-type heat exchanger which inserted twisted tape. The working parameters of the experiment were changed to between $3,000 \leq Re \leq 30,000$ turbulence regime, $0.01 \leq \varphi \leq 0.03$ *vol.%* concentrations, and $5 \leq H/D \leq 20$ twist ratio. They concluded that when compared to water, 0.03 *vol.%* concentration in all tubes with twisted tape inserts enhanced the Nusselt number by 31.28%. However, the friction factor was seen 1.23 times increase in twisted tape insert of $H/D=5$ compared to water. Esmaeilzadeh et al. [30] have experimented to investigate heat transfer and friction factor characteristics of γ-Al_2O_3/water nanofluid used in a circular tube with twisted tape inserts with various thicknesses. The experiment was realized under the $\varphi=0.5\text{-}1.0$ vol.% concentrations, $H/D=3.21$ constant twist ratio, $150 \leq Re \leq 1,600$ laminar regimes, 500 W/m^2 constant heat flux, and t=0.05-1-2 mm twisted tape thickness. According to the results inserting twisted tape enhanced the average convective heat transfer coefficient. Moreover, increasing the thickness of the twisted tape is more the enhancement of convective heat transfer coefficient.

In this numerical investigation, the heat transfer and flow characteristics using Al_2O_3/water nanofluid with different volume concentrations are carried out in four circular tubes inserted with four different twisted tape geometries. The effect of pitch ratio in twisted tape tubes, which is one of the passive methods that increase heat transfer, on heat transfer and flow properties is compared with a conventional smooth tube without twisted tapes. In addition to this situation, the addition of nanoparticles to the working fluid, which is one of the other passive methods, has been studied in detail. The data obtained as a result of combining these two passive methods under the same study are discussed in detail in order to develop advanced cooling techniques and to provide a reference for the designs of modern heat exchangers.

2. Description of physical models

2.1. Physical model

In this study, it is attempted to determine the most efficient *TPR* of twisted tape inserted in a circular tube. The study has been realized at variable parameters which *TPR* (0, 50, 100, and 200), $1000 \leq Re \leq 2000$ laminar flow regime, $0.0 \leq \varphi \leq 3.0$ *vol.%* concentrations of Al_2O_3 nanoparticle, and constant heat flux at 4357 W/m^2.

The tube inserted with twisted tape has a 3100 mm longitudinal length and 16 mm diameter. While 1600 mm of this longitudinal length is suction section, a constant heat flux of 4357 W/m^2 is applied to the remaining 1500 mm part. The geometry and boundary conditions information for present study can be seen from Figure 1. The nanofluid and water inlet temperature is 290 K and the thermophysical properties given in Table 1 are determined by this temperature value.

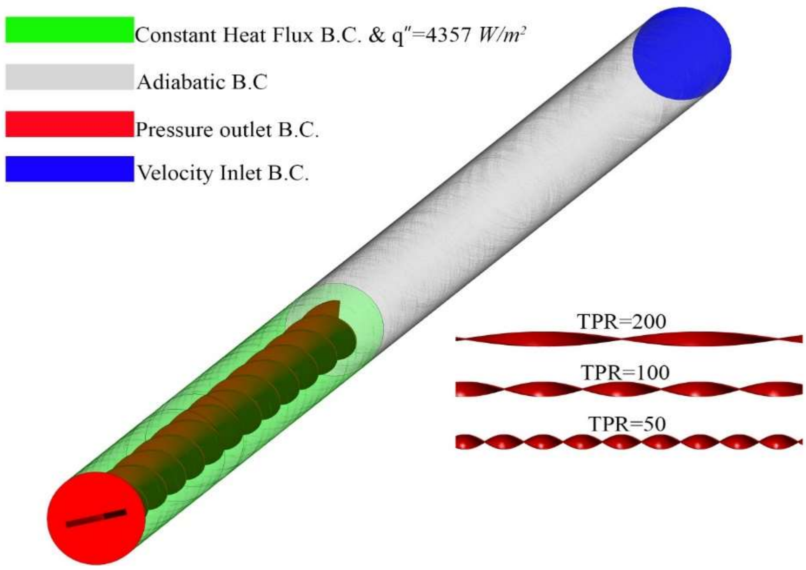

Figure 1. Geometry and boundary conditions information for present study

2.2. Governing equation

In order to solve heat transfer and flow properties of numerical study, Reynolds Averaged Navier-Stokes (RANS) equations and the energy equation are defined as the governing equations. In this study; while the single-phase approach is admitted, the fluid flow is considered in the laminar regime and the governing equations given below in Eq.(1)-(3) are solved by utilizing the following assumptions [31]:

i. Flow is considered a steady-state
ii. Nanofluid has been suspended to the water as homogenous and incompressible fluid
iii. Buoyancy effect and heat transfer realized with radiation have been neglected

Continuity equation:

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

Momentum equation:

$$\rho \frac{d\vec{V}}{dt} = \rho \vec{g} - \nabla p + \mu \nabla^2 \vec{V} \tag{2}$$

Energy equation:

$$\rho c_p \frac{dT}{dt} = k \nabla^2 T \tag{3}$$

2.3. Data reduction

The average convective heat transfer coefficient of the heated tube is given below as Eq.(4) [32]. This is required to determine the heat transfer performance.

$$h_{nf} = \frac{q''}{(T_w - T_b)} \tag{4}$$

where q" [W/m2K] is the constant heat flux, T_w [K] is the average wall temperature and T_b [K] is the average temperature of the inlet and outlet. The bulk temperature can be calculated with Eq.(5) [32]:

$$T_b = \frac{T_{in} + T_{out}}{2} \tag{5}$$

The Nu can be calculated with Eq.(6) [32]:

$$Nu_{nf} = \frac{h_{nf} \cdot D_h}{k_{nf}} \tag{6}$$

where h [W/m^{2}K] is the average convection coefficient, k [W/mK] is the thermal conductivity of the working fluid, and D_h [m] is the hydraulic diameter of tubes. The *ff* can be calculated by Eq.(7) [33]:

$$ff = \frac{\Delta P}{\left(\frac{L}{D}\right) \cdot \left(\frac{\rho \cdot V^2}{2}\right)} \tag{7}$$

where ΔP [Pa] is the pressure drop, L [m] is the length of the tube, D [m] is the diameter of the tube and ρ [kg/m3] with V [m/s] are the density and velocity of the fluid, respectively.

2.4. Nanofluid thermophysical properties

Nanofluids are produced by one or more nanoparticles mixing with the base fluid such as ethylene glycol, water, and oil. Thanks to this, the thermophysical properties such as viscosity, thermal conductivity, density, and specific heat of base fluid increase [34]. In the present study, Al_2O_3/water nanofluid and water has been used as working fluid. The thermophysical properties of Al_2O_3 nanoparticles and water have been determined and given in Table 1.

Table 1. Thermophysical properties of water and Al_2O_3 nanoparticles [35]

Fluid properties	Water	Al_2O_3
Density, ρ (kg/m^3)	998.2	3970
Specific heat, c_p (J/kgK)	4182	765
Thermal conductivity, k (W/mK)	0.6	40
Dynamic viscosity, μ (kg/ms)	1e^{-3}	-

Under these properties in order to calculate the thermophysical properties of Al_2O_3/water nanofluid following equations have been described, below.

The density of Al_2O_3/water nanofluids can be calculated by the Pak and Cho equation given in Eq.(8) [36]:

$$\rho_{nf}=(1-\varphi)\rho_{bf}+\varphi\rho_{np} \tag{8}$$

The thermal conductivity of Al_2O_3/water nanofluids can be defined as Eq.(9) [37]:

$$\frac{k_{nf}}{k_{bf}}=\frac{k_{np}+2k_{bf}-2\varphi\left(k_{bf}-k_{np}\right)}{k_{np}+2k_{bf}+\varphi\left(k_{bf}-k_{np}\right)} \tag{9}$$

The specific heat of Al_2O_3/water nanofluids can be acquired from Eq.(10) [38]:

$$c_{p_{nf}}=\frac{(1-\varphi)\left(\rho c_p\right)_{bf}+\varphi\left(\rho c_p\right)_{np}}{\rho_{nf}} \tag{10}$$

The dynamic viscosity of Al_2O_3/water nanofluids can be calculated by the Wang equation given in Eq.(11) [39]:

$$\mu_{nf}=(1+7.3\varphi+123\varphi^2)\mu_{bf} \tag{11}$$

The thermal performance enhancement rate can be obtained by Eq.(12) given below:

$$TPE=\frac{Nu_{enhanced}}{Nu_{based}} \tag{12}$$

where $Nu_{enhanced}$ and Nu_{base} denote the *Nu number* of tube geometries with and without twisted tape, respectively.

3. Numerical Method and Validation

Numerical analyses have been conducted by ANSYS Fluent 2020R2 software and utilized from SIMPLE algorithm which can carry out more fast and correct solutions [40]. While the solutions have been obtained from the second-order upwind scheme, the steady-stade solver has been used. Also, the finite-volume method performs numerical calculations by solving governing equations along with the boundary conditions. All numerical analyses have been calculated until a residual value of 10^{-6} was corrected. In order to determine mesh quality and for more correct results a lot of qualities such as the orthogonal quality, element quality, skewness, and aspect ratio have been controlled.

3.1. Mesh Convergence Study

One of the critical factors in the numerical analysis is the number of cells and quality. While the excessive cell number increases the solution time, poor mesh quality or low cell numbers causes to decrease in the accuracy of results. Therefore, a mesh convergence study is very important to obtain reasonable results within optimum solution time.

Table *2* presents the elements number, which is obtained from mesh convergence study. The mesh study has been carried out for TPR=0 at the highest *Re*. Since the difference between case3 and case4 is low in terms of *Nu*, the case3 can be considered as optimum mesh. Also, Figure2 shows the detailed mesh structure of the computational domains for each tube with twisted tape inserts. It can be seen that the denser mesh structures have been applied close to the tube wall and tapes.

Table 2. The number of cells in the mesh convergence study

Case	**1**	**2**	**3**	**4**
Mesh number	650154	1035488	*10648721*	2318474
Nu	9.8544	10.8599	*12.154*	12.146

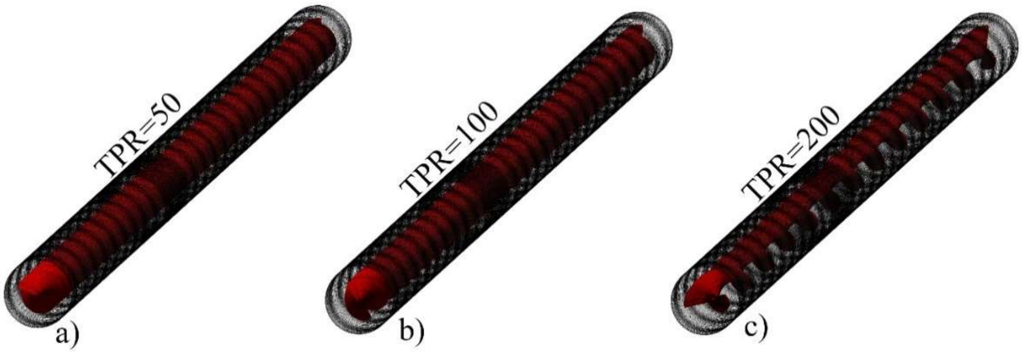

Figure 2. Mesh structure of computational domains inserted with: (a) *TPR*=50, (b) *TPR*=100 and (c) *TPR*=200.

3.2. Model Validation

After the mesh convergence study was conducted, the results obtained from the numerical analysis were validated with the literature and this validation was given in Figure3. For validation, both experimental and well-known correlations in the literature were used. While the analysis results were in average ±2.15% error margin of Gürdal et al. [41] experimental study, ±4.78% error margin of Shah-London [42] correlation in terms of *Nu*. On the other hand, the deviation of *ff* is detected by 4.12% compared with exp. data of Gürdal et al. [41]. As a result, it can be decided that numerical results are in harmony with experimental and correlation results.

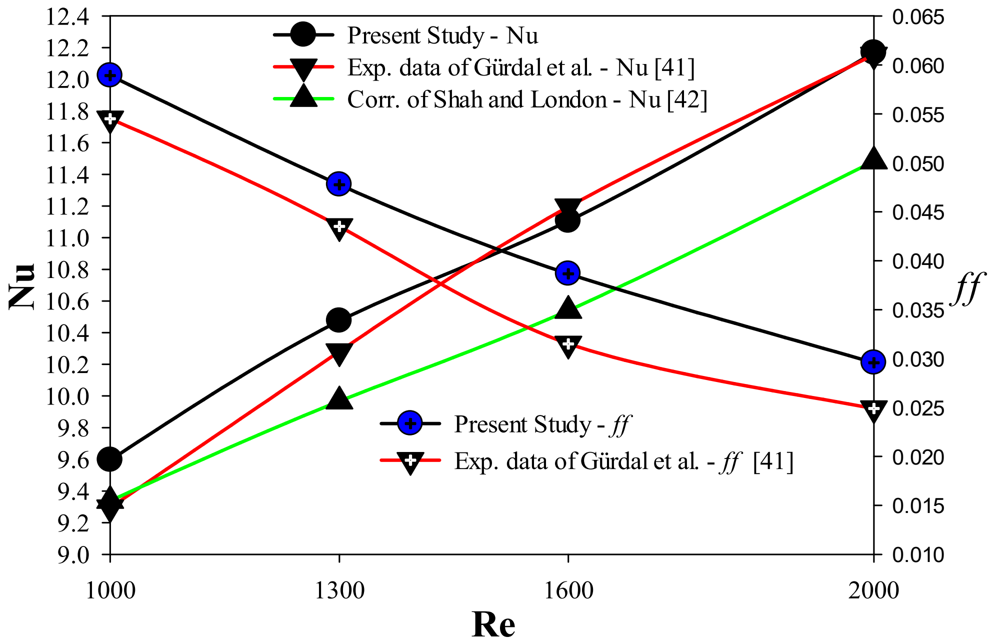

Figure 3. Validation of *Nu* and *ff* with literature

4. Results and Discussion

The numerical investigations are carried out for circular tube inserted twisted tapes with different twisted ratios under laminar flow regime and constant heat flux conditions. As a working fluid, Al_2O_3/water nanofluid which has between φ=0.0-3.0 *vol.%* concentrations were used. The results obtained from this analysis have been presented with the help of streamlines, contour, and graphics.

4.1. Effect of twisted tape

Initially, the numerical analysis was carried out with water as a working fluid in twisted tape tubes. Figure4 is presented a variation of *Nu number* and *ff* with *Re number* at different twisted tape ratios. It can be seen that the *Nu number* is enhanced as the *Re number* increases and the highest *Nu number* has been obtained in *TPR*=50, while similar results have been seen in the experimental study of Bas and Ozceylan [43]. Compared to the *TPR*=0 situation, the highest enhancement was realized as 54.36% at *Re*=2000 using TPR=50. However, decreasing in *TPR* caused an increasing pressure drop and in this situation, *ff* increases in the tube. It can be explicitly seen that as the *Re* increases, the *ff* is gradually decreasing in all *TPR*. Also, the pressure drop difference of *TPR* is almost the same as for all *Re numbers*. The highest pressure drop has been seen in *TPR*=50 at *Re*=1000 as 559.2% compared with *TPR*=0. These results are in harmony with the experimental study conducted by Eiamsa-ard et al. [44].

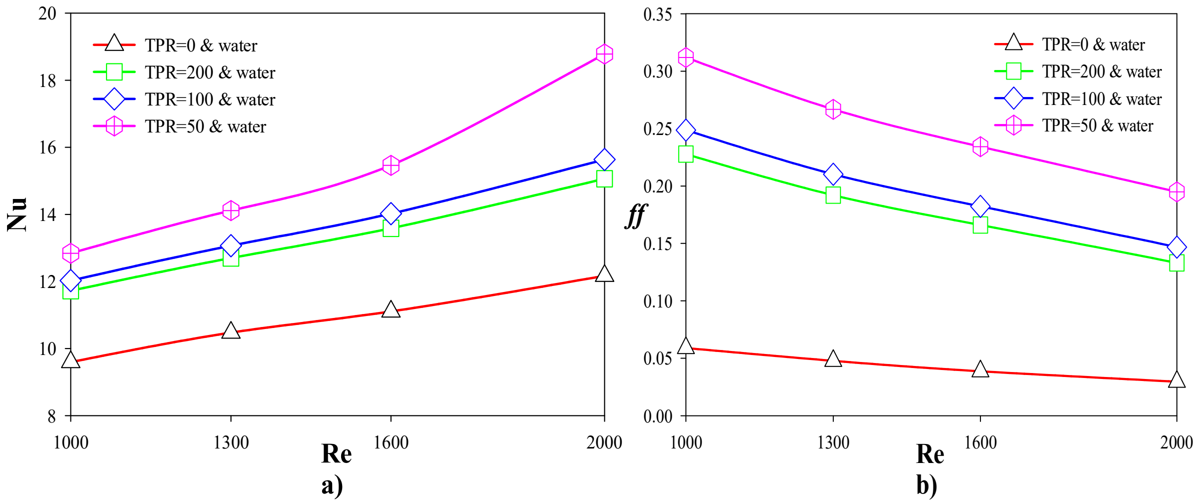

Figure 4. Variation of (a) *Nu number* and (b) *ff value* with *Re number*

The twisted tape inserted into the circular tube is generated a swirl flow which is used as a passive heat transfer enhancement technique. Due to this technique, heat transfer enhancement occurs primarily with the help of the fluid agitation and mixing induced by the cross-stream secondary circulation that is generated in the helical fluid motion [45]. Figure5 illustrates the streamline for each twisted tape geometries at *Re*=2000 and a constant φ=3.0 *vol.%* concentration. As is shown in this figure, the higher velocity value is obtained in the *TPR*=50, because using of lower twisted pitch ratio causes stronger secondary flows and so better mixing is realized in a nanofluid. Also, the swirl flows have significant effects on the velocity and temperature profiles. Decreasing of twisted pitch ratio enhances the thermal boundary layer gradient on the tube surface and the thermal boundary layer thickness reduces. So, this phenomenon provides increasing in *Nu*.

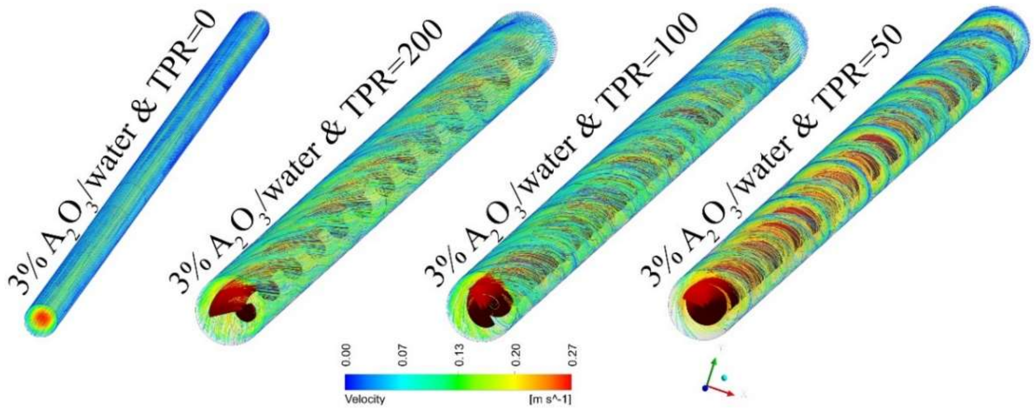

Figure 5. Effect of TPR on the swirl flow velocity in the tube at Re=2000 and φ=3.0 vol.% concentration

The *Nu* distribution for tubes at different *TPR* at *Re*=2000 and *φ*=3.0 *vol.%* Al_2O_3 nanofluid is shown in Figure6. When this figure is observantly examined, the convection heat transfer decreases significantly in the flow direction for all *TPR*. However, it can be seen that the *Nu* in *TPR*=50 which is the lowest twist tape rate is higher than compared to other *TPRs* under the same conditions, and convection heat transfer increases towards the tube outlet at *TPR*=50. This situation reveals that the lower twist ratio leads to higher tangential contact between the swirling flow and the tube surface and the *Nu* increases with the reduction of *TPR* [46].

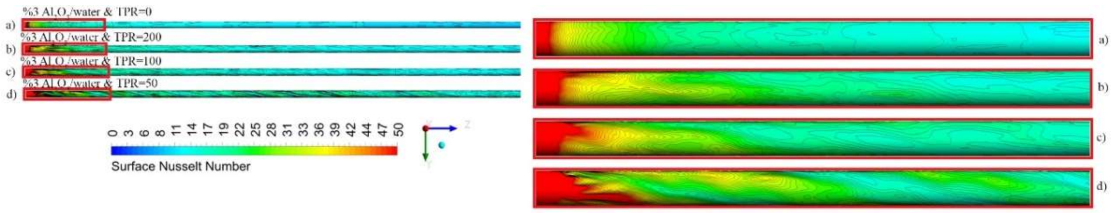

Figure 6. Surface *Nu number* distribution for all *TPR* at *Re*=2000 and φ=3.0 *vol.%* concentration

Figure7 presents velocity contour over different cross-sections located at different z-axis of the tube at different TPR at Re=2000, and 3.0 *vol.%* concentration. When carefully observing the contours, it can be seen that the intensity of velocity at the inlet gradually decreases through the outlet due to an increase in flow resistance. Also, the cross-section contour on the same z-axis for each *TPRs* has the almost same velocity distribution.

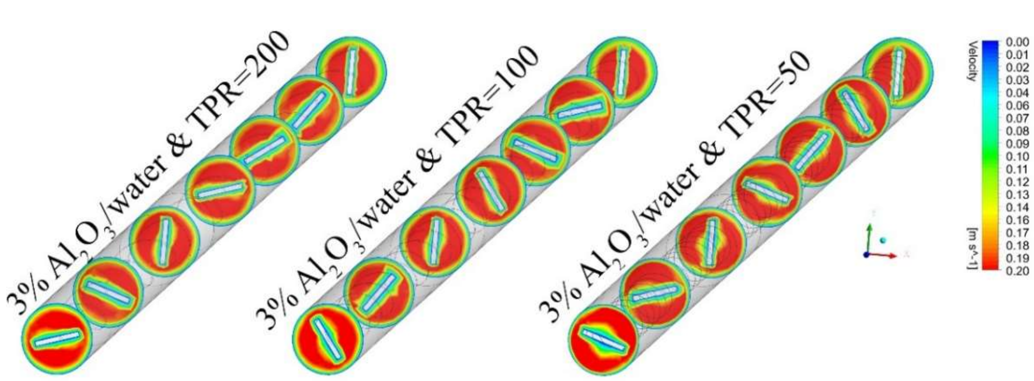

Figure 7. Cross-section velocity contours for all *TPR* at *Re*=2000 and φ=3.0 *vol.%* concentration

4.2. Effect of nanofluid

In order to comprehensively handle the *TPR*=50 situation which exhibited the higher thermal performance, variation of *Nu* and *ff value* with *Re* have been shown Figure8. According to Figure8(a), the *Nu number* increased with nanofluid concentration through the increase in the thermophysical properties of the working fluid. The highest *Nu* for *TPR*=50 was obtained at *φ*=3.0 *vol.%* concentration as 4.39% compared with water. One of the most important factors which caused occur this phenomenon is added nanoparticles which have greater thermal conductivity compared to water improve the thermal conductivity coefficient. Furthermore, the addition of nanoparticles increases the viscosity caused by the *ff* and so the velocity gradient increases to close the tube wall [19], [47], [48].

When investigating Figure8(b), the *ff value* at *TPR*=50 with different nanofluid concentrations is almost constant at different *Re numbers*. It can be seen that as the *Re number* increases *ff value* is decreasing, continuously. The underlying reason for this issue is that as the *Re number* increase the thickness of the boundary layer decreases. This is because the viscosity loses its effect in the area it affects and the shear stress decreases with the velocity gradient [19]. The same results have been obtained from an experimental study conducted by Jaisankar et al. [49].

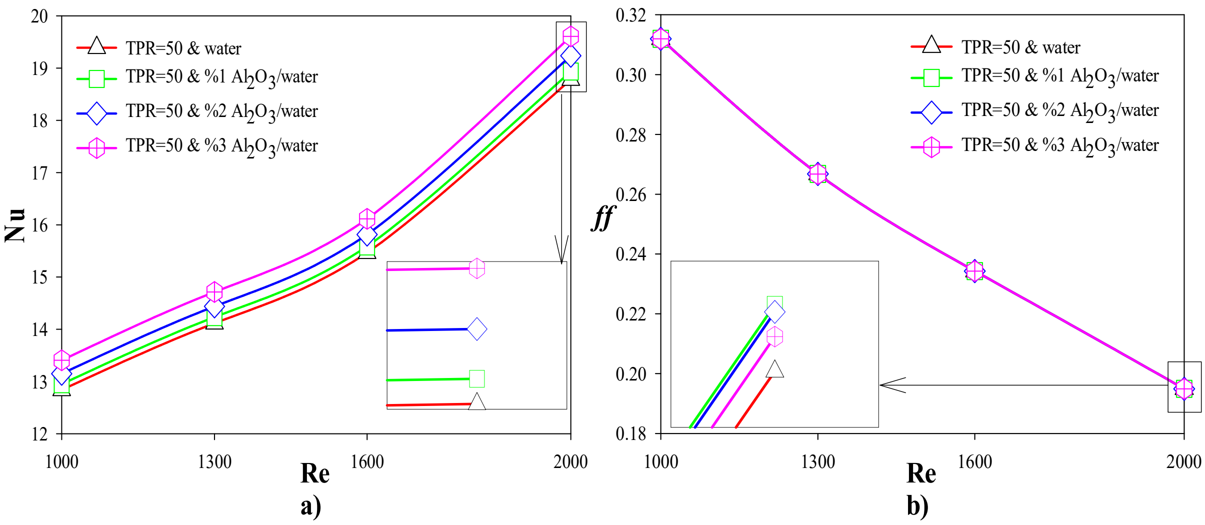

Figure 8. Variation of (a) *Nu number* and (b) *ff value* with *Re number* at different *φ* and *TPR*=50

4.3. Thermal performance enhancement analysis

In Figure 9, the thermal performance enhancement (*TPE*) of *TPR*=50 geometry where the highest convective heat transfer realized and *TPR*=0 at different nanofluid concentrations is given graphically. The geometry with 0.0 *vol.%* concentration and *TPR*=0 is accepted as a reference in this assessment. When the graph is examined, it can be seen that as the nanofluid concentration increases in *TPR*=0 geometries, the *TPE* also increases. However, this increased rate in *TPR*=50 geometries accelerates especially after *Re*=1600. In addition, even if the highest nanofluid ratio is used at *TPR*=0, the convection heat transfer enhancement rate in the twisted tape tube in which water is used as the working fluid cannot exceed the rate of increase. The convective heat transfer enhancement in *TPR*=50 & *φ*=3.0 vol.%. at *Re*=2000 was realized by at least 44.34% compared to *TPR*=0 & water. When the effect of the twisted tape ratio on the thermal performance was examined, the *TPR*=0 and 50 geometries were evaluated at the same nanofluid concentration ratio and the highest increase in convective heat transfer was realized by 53.39% at the *φ*=3.0 *vol.%* at *Re*=2000. The rate of increase at *φ*=1.0 and 2.0 *vol.%* concentrations is 51.96% and 53.08%, respectively. In addition, it is observed that the *TPE* value increases as the *Re* increases for all cases.

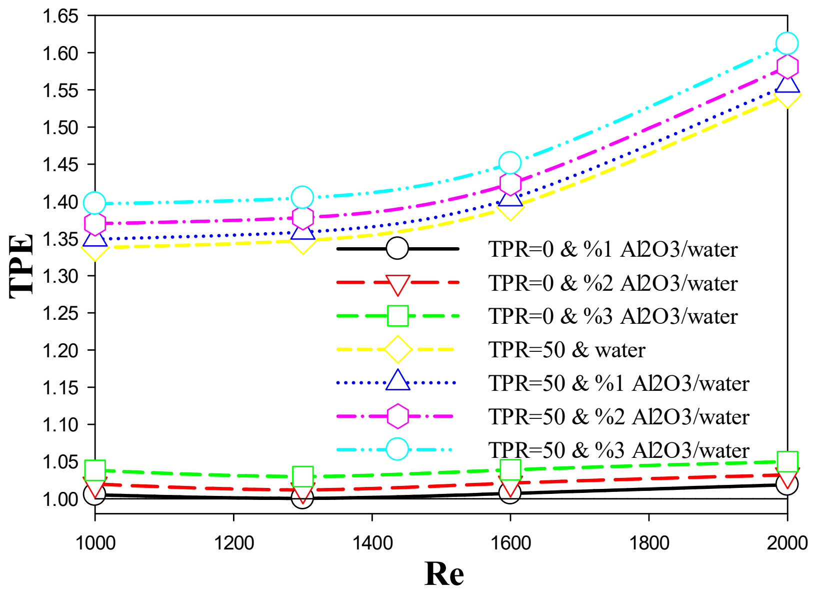

Figure 9. Variation of *TPE* number with *Re number* for different concentrations

5. Conclusions

Heat transfer characteristics and hydrodynamical analysis of twisted tape circular tube using Al_2O_3/water nanofluid with different nanoparticle concentrations ($0.0 \leq \varphi \leq 3.0$ *vol.%*) and laminar flow regime ($1000 \leq Re \leq 2000$) have been investigated numerically. In this study, circular tubes were handled under four different twist ratios (*TPR*=0, 50, 100, and 200) and computational analysis has been solved to determine the thermal and hydrodynamic properties of fluids.

The obtained results of this numerical study can be summarized as follows:

- When investigating twisted tape geometry, the highest *Nu* has been obtained in *TPR*=50 for each cases. TPR=50 & water presents the highest enhancement by 54.36% at *Re*=2000 and compared to the *TPR*=0 & water. The highest pressure drop has been realized in TPR=50 geometry at *Re*=1000 as 559.2% compared with *TPR*=0. These two results are in harmony with experimental studies in the literature.
- Because a lower twisted pitch ratio causes stronger secondary flows and better mixing, the higher velocity and temperature gradient associated with synergy angle was obtained using *TPR*=50.
- It can be seen that the *Nu* in *TPR*=50 is higher than compared other *TPRs* under the same conditions. This situation is the proof of a lower twist ratio leads to higher tangential contact between the swirling flow and the tube surface and so the *Nu* increases.
- The highest *Nu* was obtained for *TPR*=50 & φ=3.0 *vol.%* at *Re*=2000 by 61.15% compared with TPR=0 & water at same *Re*.
- The highest *TPE* was realized using TPR=50 & φ=3.0 *vol.%* at *Re*=2000 conditions as 1.61.

Acknowledgment(s)
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] J. Albadr, S. Tayal, ve M. Alasadi, “Heat transfer through heat exchanger using Al2O3 nanofluid at different concentrations”, *Case Stud. Therm. Eng.*, c. 1, sayı 1, ss. 38–44, 2013, doi:

10.1016/j.csite.2013.08.004.

[2] M. Sheikholeslami, R. ul Haq, A. Shafee, Z. Li, Y. G. Elaraki, ve I. Tlili, "Heat transfer simulation of heat storage unit with nanoparticles and fins through a heat exchanger", *Int. J. Heat Mass Transf.*, c. 135, ss. 470–478, 2019, doi: 10.1016/j.ijheatmasstransfer.2019.02.003.

[3] P. Promvonge, N. Koolnapadol, M. Pimsarn, ve C. Thianpong, "Thermal performance enhancement in a heat exchanger tube fitted with inclined vortex rings", *Appl. Therm. Eng.*, c. 62, sayı 1, ss. 285–292, 2014, doi: 10.1016/j.applthermaleng.2013.09.031.

[4] A. Sözen, A. Khanları, ve E. Çiftçi, "Experimental and numerical investigation of heat transfer enhancement in a plate heat exchanger using a fly ash nanofluid", *Int. J. Renew. Energy Dev.*, c. 8, ss. 27–32, 2019, doi: https://doi.org/10.14710/ijred.8.1.27-32.

[5] M. Gürdal, H. K. Pazarlıoğlu, M. Tekir, K. Arslan, ve E. Gedik, "Numerical investigation on turbulent flow and heat transfer characteristics of ferro-nanofluid flowing in dimpled tube under magnetic field effect", *Appl. Therm. Eng.*, c. 200, sayı June 2021, 2022, doi: 10.1016/j.applthermaleng.2021.117655.

[6] B. Horacek, K. T. Kiger, ve J. Kim, "Single nozzle spray cooling heat transfer mechanisms", *Int. J. Heat Mass Transf.*, c. 48, sayı 8, ss. 1425–1438, 2005, doi: 10.1016/j.ijheatmasstransfer.2004.10.026.

[7] S. N. Sarada, A. S. R. Raju, K. K. Radha, ve L. S. Sunder, "Enhancement of heat transfer using varying width twisted tape inserts", *Int. J. Eng. Sci. Technol.*, c. 2, sayı 6, ss. 107–118, 2011, doi: 10.4314/ijest.v2i6.63702.

[8] T. Alam ve M. H. Kim, "A comprehensive review on single phase heat transfer enhancement techniques in heat exchanger applications", *Renew. Sustain. Energy Rev.*, c. 81, sayı June 2017, ss. 813–839, 2018, doi: 10.1016/j.rser.2017.08.060.

[9] M. T. Naik, G. R. Janardana, ve L. S. Sundar, "Experimental investigation of heat transfer and friction factor with water-propylene glycol based CuO nanofluid in a tube with twisted tape inserts", *Int. Commun. Heat Mass Transf.*, c. 46, ss. 13–21, 2013, doi: 10.1016/j.icheatmasstransfer.2013.05.007.

[10] N. H. Abu-Hamdeh, K. H. Almitani, A. A. Gari, A. Alimoradi, A. Ahmadian, ve D. Baleanu, "Hydrodynamic analysis of a heat exchanger with crosscut twisted tapes and filled with thermal oil-based SWCNT nanofluid: applying ANN for prediction of objective parameters", *J. Therm. Anal. Calorim.*, c. 145, sayı 4, ss. 2163–2176, 2021, doi: 10.1007/s10973-020-10521-4.

[11] G. Duursma, K. Sefiane, ve A. Kennedy, "Experimental studies of nanofluid droplets in spray cooling", *Heat Transfer Engineering*, c. 30, sayı 13. ss. 1108–1120, 2009, doi: 10.1080/01457630902922467.

[12] M. T. Adiwibowo, M. Ibadurrohman, ve Slamet, "Synthesis of Zno Nanoparticles and their nanofluid stability in the presence of a Palm Oil-Based Primary Alkyl Sulphate surfactant for detergent application", *Int. J. Technol.*, c. 9, sayı 2, ss. 307–316, 2018, doi: 10.14716/ijtech.v9i2.1065.

[13] H. W. Xian, N. A. C. Sidik, ve G. Najafi, "Recent state of nanofluid in automobile cooling systems", *J. Therm. Anal. Calorim.*, c. 135, sayı 2, ss. 981–1008, 2019, doi: 10.1007/s10973-018-7477-3.

[14] A. Ijam ve R. Saidur, "Nanofluid as a coolant for electronic devices (cooling of electronic devices)", *Appl. Therm. Eng.*, c. 32, sayı 1, ss. 76–82, 2012, doi: 10.1016/j.applthermaleng.2011.08.032.

[15] G. Colangelo, E. Favale, P. Miglietta, A. de Risi, M. Milanese, ve D. Laforgia, "Experimental test of an innovative high concentration nanofluid solar collector", *Appl. Energy*, c. 154, ss. 874–881, 2015, doi: 10.1016/j.apenergy.2015.05.031.

[16] M. Gürdal, K. Arslan, E. Gedik, ve A. Adriana, "Effects of using nanofluid , applying a magnetic field , and placing turbulators in channels on the convective heat transfer : A comprehensive review", *Renew. Sustain. Energy Rev.*, c. 162, sayı April, s. 112453, 2022, doi: 10.1016/j.rser.2022.112453.

[17] A. Hasanpour, M. Farhadi, ve K. Sedighi, "A review study on twisted tape inserts on turbulent flow heat exchangers: The overall enhancement ratio criteria", *Int. Commun. Heat Mass Transf.*, c. 55, ss. 53–62, 2014, doi: 10.1016/j.icheatmasstransfer.2014.04.008.

[18] S. Tabatabaeikia, H. A. Mohammed, N. Nik-Ghazali, ve B. Shahizare, "Heat Transfer Enhancement by Using Different Types of Inserts", *Advances in Mechanical Engineering*, c. 2014. 2014, doi:

10.1155/2014/250354.

[19] W. He, D. Toghraie, A. Lotfipour, F. Pourfattah, A. Karimipour, ve M. Afrand, "Effect of twisted-tape inserts and nanofluid on flow field and heat transfer characteristics in a tube", *Int. Commun. Heat Mass Transf.*, c. 110, sayı December 2019, 2020, doi: 10.1016/j.icheatmasstransfer.2019.104440.

[20] K. Wongcharee ve S. Eiamsa-ard, "Enhancement of heat transfer using CuO/water nanofluid and twisted tape with alternate axis", *Int. Commun. Heat Mass Transf.*, c. 38, sayı 6, ss. 742–748, 2011, doi: 10.1016/j.icheatmasstransfer.2011.03.011.

[21] S. Eiamsa-ard ve K. Kiatkittipong, "Heat transfer enhancement by multiple twisted tape inserts and TiO 2 / water nano fl uid", c. 70, ss. 896–924, 2014, doi: 10.1016/j.applthermaleng.2014.05.062.

[22] M. Bahiraei, N. Mazaheri, ve F. Aliee, "Second law analysis of a hybrid nano fl uid in tubes equipped with double twisted tape inserts", *Powder Technol.*, c. 345, ss. 692–703, 2019, doi: 10.1016/j.powtec.2019.01.060.

[23] W. H. Azmi, K. V Sharma, P. K. Sarma, R. Mamat, ve S. Anuar, "Comparison of convective heat transfer coef fi cient and friction factor of TiO 2 nano fl uid fl ow in a tube with twisted tape inserts", *Int. J. Therm. Sci.*, c. 81, ss. 84–93, 2014, doi: 10.1016/j.ijthermalsci.2014.03.002.

[24] R. Aghayari, H. Maddah, S. M. Pourkiaei, M. H. Ahmadi, L. Chen, ve M. Ghazvini, "Theoretical and experimental studies of heat transfer in a double-pipe heat exchanger equipped with twisted tape and nanofluid", *Eur. Phys. J. Plus*, c. 135, sayı 2, ss. 1–26, 2020, doi: 10.1140/epjp/s13360-020-00252-8.

[25] Z. Li, M. Sheikholeslami, M. Jafaryar, A. Shafee, ve A. J. Chamkha, "Investigation of nanofluid entropy generation in a heat exchanger with helical twisted tapes", *J. Mol. Liq.*, c. 266, ss. 797–805, 2018, doi: 10.1016/j.molliq.2018.07.009.

[26] S. A. Farshad ve M. Sheikholeslami, "Nanofluid flow inside a solar collector utilizing twisted tape considering exergy and entropy analysis", *Renew. Energy*, c. 141, ss. 246–258, 2019, doi: 10.1016/j.renene.2019.04.007.

[27] L. S. Sundar ve K. V Sharma, "International Journal of Heat and Mass Transfer Turbulent heat transfer and friction factor of Al 2 O 3 Nanofluid in circular tube with twisted tape inserts", *Int. J. Heat Mass Transf.*, c. 53, sayı 7–8, ss. 1409–1416, 2010, doi: 10.1016/j.ijheatmasstransfer.2009.12.016.

[28] H. Safikhani ve F. Abbasi, "Numerical study of nanofluid flow in flat tubes fitted with multiple twisted tapes", *Adv. Powder Technol.*, c. 26, sayı 6, ss. 1609–1617, 2015, doi: 10.1016/j.apt.2015.09.002.

[29] P. V. Durga Prasad ve A. V. S. S. K. S. Gupta, "Experimental investigation on enhancement of heat transfer using Al2O3/water nanofluid in a u-tube with twisted tape inserts", *Int. Commun. Heat Mass Transf.*, c. 75, ss. 154–161, 2016, doi: 10.1016/j.icheatmasstransfer.2016.03.019.

[30] E. Esmaeilzadeh, H. Almohammadi, A. Nokhosteen, A. Motezaker, ve A. N. Omrani, "Study on heat transfer and friction factor characteristics of γ-Al2O3/water through circular tube with twisted tape inserts with different thicknesses", *Int. J. Therm. Sci.*, c. 82, sayı 1, ss. 72–83, 2014, doi: 10.1016/j.ijthermalsci.2014.03.005.

[31] E. Taskesen, M. Tekir, E. Gedik, ve K. Arslan, "Numerical investigation of laminar forced convection and entropy generation of Fe3O4/water nanofluids in different cross-sectioned channel geometries", *J. Therm. Eng.*, c. 7, sayı 7, ss. 1752–1767, 2021, doi: 10.18186/thermal.1025984.

[32] M. Favre-marinet ve S. Tardu, *Convective Heat Transfer*. .

[33] E. Khodabandeh, M. R. Safaei, S. Akbari, O. A. Akbari, ve A. A. A. A. Alrashed, "Application of nanofluid to improve the thermal performance of horizontal spiral coil utilized in solar ponds: Geometric study", *Renew. Energy*, c. 122, ss. 1–16, Tem. 2018, doi: 10.1016/j.renene.2018.01.023.

[34] S. U. S. Choi, "Enhancing thermal conductivity of fluids with nanoparticles", *Am. Soc. Mech. Eng. Fluids Eng. Div. FED*, c. 231, ss. 99–105, 1995.

[35] M. Sheikholeslami ve Z. Ebrahimpour, "International Journal of Thermal Sciences Thermal improvement of linear Fresnel solar system utilizing Al 2 O 3 -water nanofluid and multi-way twisted

tape", *Int. J. Therm. Sci.*, c. 176, sayı December 2021, s. 107505, 2022, doi: 10.1016/j.ijthermalsci.2022.107505.

[36] B. C. Pak ve Y. I. Cho, "Hydrodynamic And Heat Transfer Study of Dispersed Fluids With Submicron Metallic Oxide Particles Transfer Study of Dispersed Fluids with Submicron Metallic Oxide", c. 6152, 2007, doi: 10.1080/08916159808946559.

[37] Y. Xuan ve W. Roetzel, "Conceptions for heat transfer correlation of nano ¯ uids", c. 43, ss. 3701–3707, 2000.

[38] X. Wang ve X. Xu, "Thermal Conductivity of Nanoparticle – Fluid Mixture", c. 13, sayı 4, 1999.

[39] A. Bejan, *Convection heat transfer*, Fourth Edi. Durham, North Carolina, 2013.

[40] M. Sheikholeslami *vd.*, "Journal of Molecular Liquids", c. 291, 2019, doi: 10.1016/j.molliq.2019.111283.

[41] M. Gürdal, H. K. Pazarlıoğlu, M. Tekir, F. M. Altunay, K. Arslan, ve E. Gedik, "Implementation of hybrid nanofluid flowing in dimpled tube subjected to magnetic field", *Int. Commun. Heat Mass Transf.*, c. 134, s. 106032, 2022, doi: 10.1016/j.icheatmasstransfer.2022.106032.

[42] R. K. Shah ve A. L. London, *Laminar Flow Forced Convection in Ducts: A Source Book for Compact Heat Exchanger Analytical Data*, c. Suppl. 1. 1978.

[43] H. Bas ve V. Ozceyhan, "Heat transfer enhancement in a tube with twisted tape inserts placed separately from the tube wall", *Exp. Therm. Fluid Sci.*, c. 41, ss. 51–58, 2012, doi: 10.1016/j.expthermflusci.2012.03.008.

[44] S. Eiamsa-ard, K. Wongcharee, P. Eiamsa-ard, ve C. Thianpong, "Heat transfer enhancement in a tube using delta-winglet twisted tape inserts", *Appl. Therm. Eng.*, c. 30, sayı 4, ss. 310–318, 2010, doi: 10.1016/j.applthermaleng.2009.09.006.

[45] R. M. Manglik ve A. E. Bergles, *Swirl flow heat transfer and pressure drop with twisted-tape inserts*, c. 36, sayı C. 2003.

[46] S. D. Salman, A. A. H. Kadhum, M. S. Takriff, ve A. B. Mohamad, "Heat Transfer Enhancement of Laminar Nanofluids Flow in a Circular Tube Fitted with Parabolic-Cut Twisted Tape Inserts", c. 2014, 2014.

[47] R. Aghayari, H. Maddah, S. M. Pourkiaei, M. H. Ahmadi, L. Chen, ve M. Ghazvini, "Theoretical and experimental studies of heat transfer in a double-pipe heat exchanger equipped with twisted tape and nanofluid", *European Physical Journal Plus*, c. 135, sayı 2. 2020, doi: 10.1140/epjp/s13360-020-00252-8.

[48] M. Sheikholeslami, S. A. Farshad, M. B. Gerdroodbary, ve A. H. Alavi, "Impact of new multiple twisted tapes on treatment of solar heat exchanger", *Eur. Phys. J. Plus*, c. 137, sayı 1, 2022, doi: 10.1140/epjp/s13360-021-02157-6.

[49] S. Jaisankar, T. K. Radhakrishnan, ve K. N. Sheeba, "Experimental studies on heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with spacer at the trailing edge of twisted tapes", *Appl. Therm. Eng.*, c. 29, sayı 5–6, ss. 1224–1231, 2009, doi: 10.1016/j.applthermaleng.2008.06.009.